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Hertz, an imaging polarimeter

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ABSTRACT

The University of Chicago polarimeter, Hertz, is designed for observations at the Caltech Submillimeter Observatory in the 350 μm atmospheric window. Initial observations with this instrument, the first array polarimeter for submillimeter observations, have produced over 700 measurements at 3σ or better. This paper summarizes the characteristics of the instrument, presents examples of its performance including polarization maps of molecular clouds and regions near the Galactic center, and outlines the opportunities for improvements with emphasis on requirements for mapping widely extended sources.

Keywords: polarimeter, far-infrared, submillimeter, dust emission, magnetic fields, interstellar medium

1. INTRODUCTION

Observations with the far-infrared and submillimeter polarimeters developed at the University of Chicago have shown that the thermal emission from dense interstellar clouds is polarized, typically to a degree of ~0.5–4%[1], and that the polarization usually varies smoothly in both angle and degree over the entire mapped area of a molecular cloud. The results have been used to infer the role of magnetic fields in star formation and other astrophysical processes[2–7], and to establish properties of interstellar dust grains[8]. Observations at the Caltech Submillimeter Observatory with Hertz, the most recent of these polarimeters, have made it possible to compare data at 350 μm with earlier results at 60 μm and 100 μm obtained on the Kuiper Airborne Observatory with the U of Chicago polarimeter, Stokes[9]. In some cases it is possible to extend the comparisons to longer submillimeter wavelengths and to results in the mid-infrared. These comparisons show that far-infrared/submillimeter polarization spectra can vary considerably from object to object (Fig. 1). Measurements of such spectra are opening up a promising field of investigation.

The initial results of imaging polarimetry and spectropolarimetry have provided a strong incentive for continuing advances in instrumentation over a wide range of wavelengths. Significant improvements in accuracy, area coverage, and spatial resolution should be attainable.

The University of Chicago polarimeters[9–14] have been designed to detect two components of polarization simultaneously. That feature of the design has been essential for the success of the instruments. Because fluctuations in atmospheric transmission affect both components equally, the noise due to the fluctuations is almost entirely removed when taking the difference over the sum of the two polarization signals.

Hertz is the first submillimeter polarimeter to incorporate arrays of detectors: one array for each component. The introduction of arrays has made it necessary to modify the observing and analyzing techniques and to expand the electronics, but these complications have been well rewarded with improvements in the quality and quantity of the data. The instrument itself has been described in earlier reports[13,14]. In this paper we give a brief review of the specifications and present examples of its current performance. We also discuss opportunities for improvements. In particular we discuss the importance of doing polarimetry on widely extended objects and the problems that must be solved to gain that capability.

2. GENERAL DESCRIPTION

A schematic design of the optics is shown in Figure 2. The optical and performance specification are presented in Table 1. Details have been presented in the papers by Schleuning et al.[13] and Dowell et al.[14].

Table 1. Selected Characteristics of the CSO Telescope and Hertz

Telescope		
	Diameter	10.4 meters
	F-ratio at focal plane	4.48
	Plate scale	4.6 arcsec/mm
	Chopping frequency	3 Hz
	Chopping amplitude	6 arcmin
Hertz		
	arrays: layout	6 × 6 with corners omitted
	pixel spacing	17.8 arcsec
	beam diameter	20 arcsec (fwhm)
	optics: $\lambda^{-2}\int A \cdot d\Omega$	2.5
	polarization efficiency	95 %
	halfwave plate	X-cut quartz, 3.6 mm thick
NEFD at τ = 0.05 (225 Ghz)		3–4 Jy/ $\sqrt{\text{Hz}}$ [τ(350 μm) ≈ 25 τ(225 Ghz)]

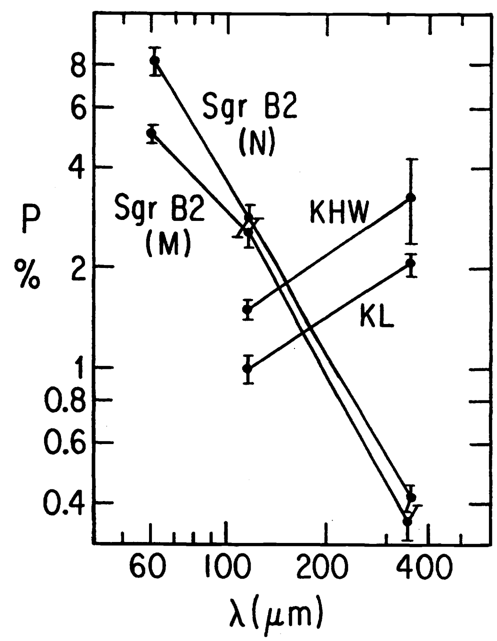


Fig 1 First far-infrared/submillimeter polarization spectra: results for the cloud cores KL and KHW in Orion, and M (Main) and N (North) in Sgr B2 (Data from ref's 3 and 4)

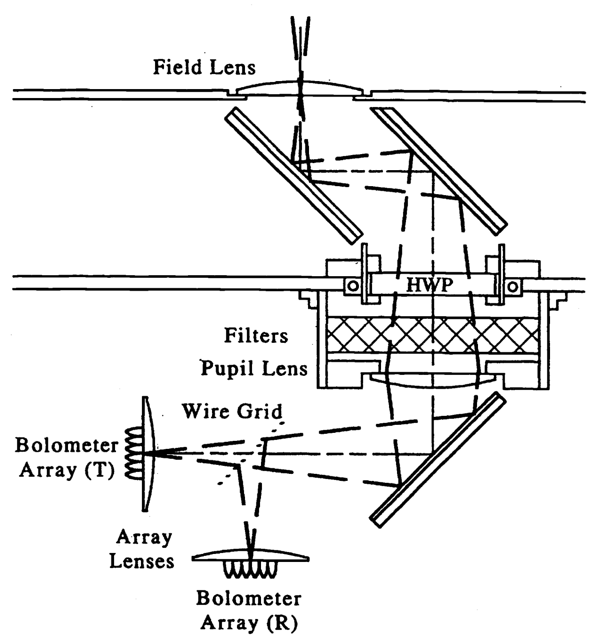


Fig 2 Schematic diagram of the optics for Hertz. The detector arrays are cooled to 300 mK; all other optical elements are cooled to 4K. A field lens at the focal plane of the telescope reimages the primary onto the pupil lens. The halfwave plate (HWP) is turned about its axis in 30° steps. The HWP, spectral filter, and pupil lens are near an image of the primary. A wire grid reflects one component of polarization onto the R-array, and transmits the other component to the T-array. The array lenses direct the beam from each Winston collector onto the pupil. [Figure from Schleuning et al.[13] Copyright 1997, Astronomical Society of the Pacific; reproduced with permission]

The halfwave plate, spectral filters, and re-imaging lens are placed as near as possible to an image of the primary so that inhomogeneities will not mimic the effect of polarized signals[15]. The detectors are arranged in 32-pixel arrays. The beam size, as determined from observation of planets, is 20 arcsec (fwhm). This represents a compromize between signal and resolution. The footprint of the array on the sky is approximately 2×2 arcmin.

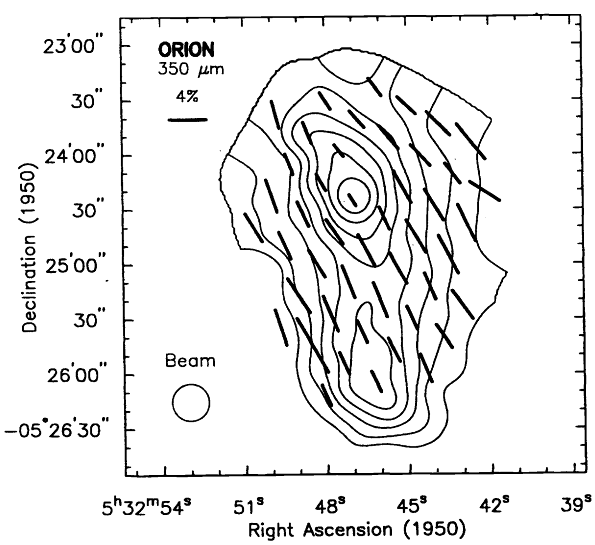
At the focal plane, the radiation is concentrated into cylindrical detector cavities by Winston collectors. These collectors are the same ones formerly used in the airborne polarimeter, Stokes[9], at 60 μm and 100 μm. They are undersized for 350 μm observations and may be responsible for a significant loss of throughput (albeit at a savings in dollars) when installed in Hertz. (Current quantum efficiency is 3.4%.)

The basic operation is standard photometric measurements with chopping (~3 Hz) and beam switching (~0.1 Hz) at each of six 30° steps of the halfwave plate. This set of operations takes about 5 minutes. The whole instrument is rotated to keep the image of the source in a fixed orientation on the arrays. In order to solve for the instrument polarization, the telescope polarization, and the source polarization one follows a sequence of operations described by Platt et al.[9] involving 90° rotations of the instrument and diplacements of the image by one or two pixels along the rows and columns of the arrays.

3. IMAGING POLARIMETRY

In Figures 3–5 we show examples of imaging polarimetry with Hertz. Most of the observations have been of the central regions of bright Galactic clouds. But as is evident from the map of the Galactic center, shown in Figure 5, it is feasible even with our present detector arrays to map relatively faint regions at relatively large air mass.

The importance of low systematic errors, now <0.2%, is illustrated in Figure 6, a histogram of the degrees of polarization measured in 12 Galactic clouds. Although the histogram shows only a distribution for the particular regions we have selected for our observations it represents the best guide we can provide for judging the precision required for submillimeter polarimetry.



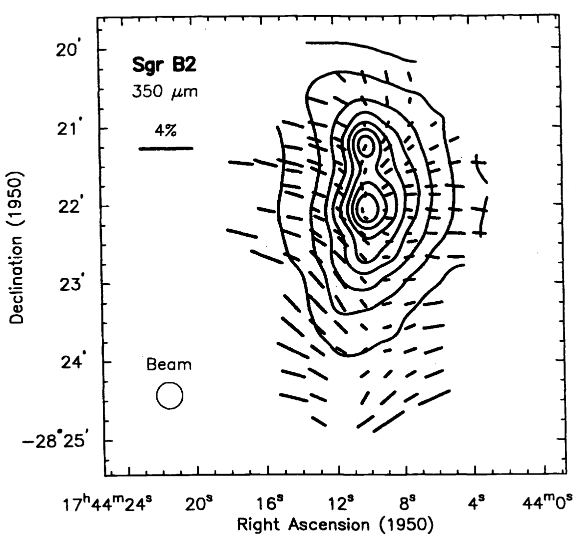


Fig 3 Examples of mapping polarimetry with Hertz. The vectors, all $\geq 3\sigma$, show the degree and direction of the polarization (E-vectors) of the emitted radiation. The flux density contours are derived from the same data by adding the signals for the two components of polarization. The Orion map is from Schleuning et al[5].

4. FUTURE UPGRADES

Although Hertz has been productive, its performance is still far below what could be achieved. The most obvious improvement is to replace the current bolometer arrays with state-of-the-art arrays such as those being developed for photometers at the CSO, the LMT, and SOFIA. We call attention to the papers at this conference by Moseley[17] and Mauskopf[18] on the development of new-technology arrays.

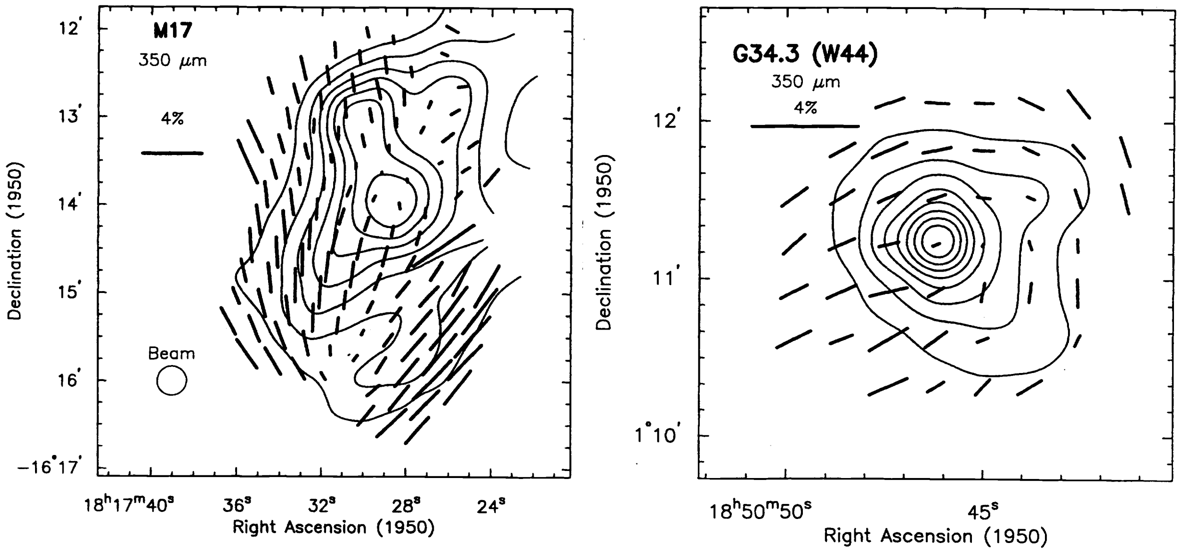


Fig 4 More examples of mapping polarimetry with Hertz. Vectors and contours as described in Fig 3.

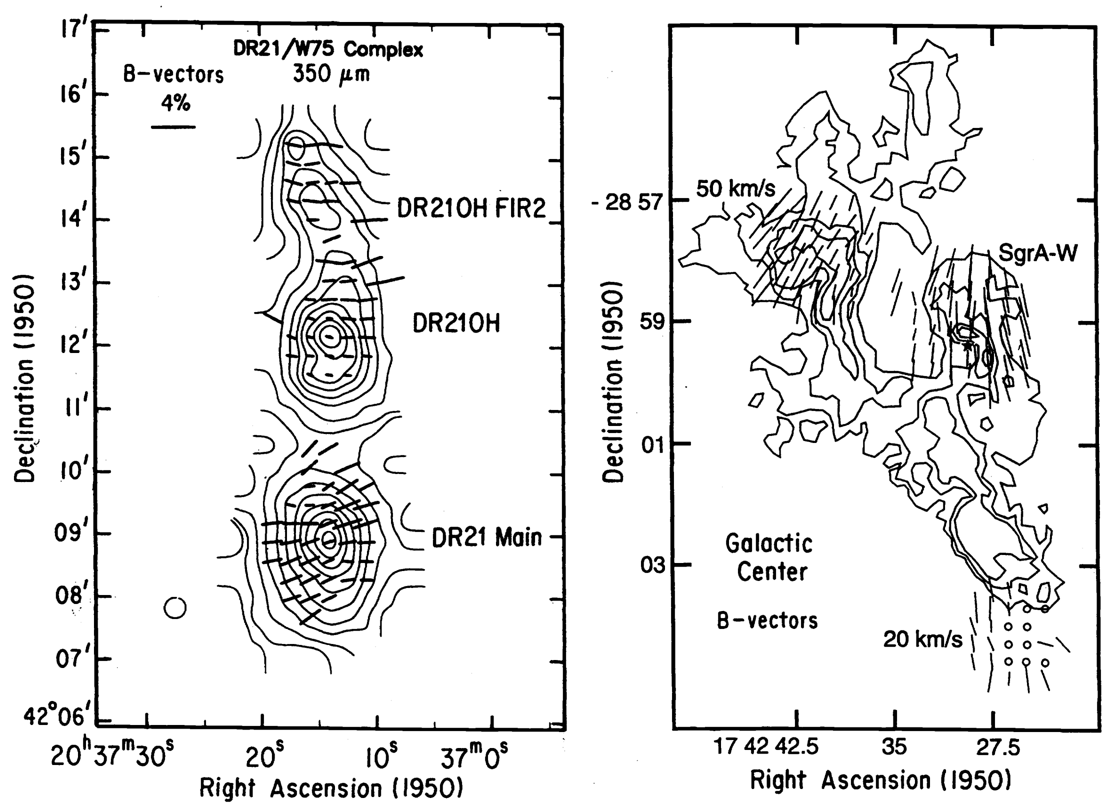
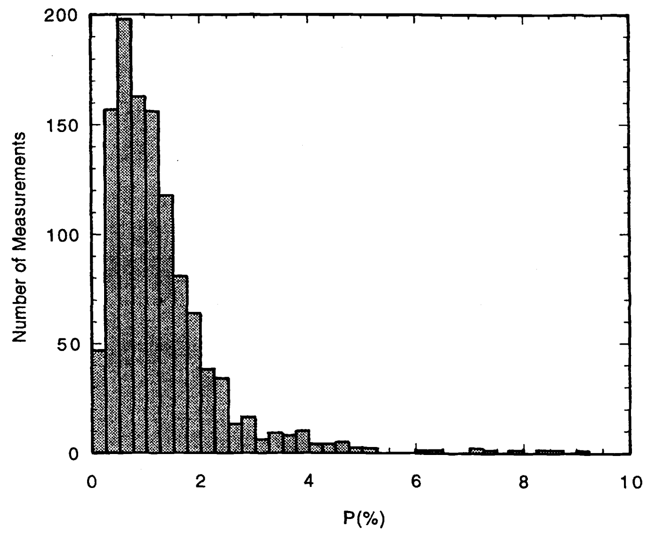


Fig 5 More examples of polarization mapping with Hertz. In this figure, unlike Figures 3 and 4, the vectors have been rotated 90° to show the inferred direction of the magnetic field (i.e. B-vectors). Again, all vectors are of $\geq 3\ \sigma$ significance. Open circles (Galactic center map) denote upper limits below 1% (nominal value + 2 × nominal error < 1%). The flux density contours in the map of DR21 are derived from the polarization data as in the maps of Figures 3 and 4. In the map of the Galactic center, by Novak et al.[20], the flux density contours are from the 800 μm map of Dent et al.[16].

Fig 6 Distribution in degrees of polarization at 350 μm for a sample of 1144 measurements including points with low signal to noise. The median polarization is 1.0%. The median statistical error is 0.3%. The systematic error is <0.2%.



By incorporating modern arrays it should become feasible to reduce the beam size of Hertz on the CSO from 20 arcsec to <10 arcsec while achieving improved signal to noise on faint objects. Because of the rigid construction of the new arrays, one can greatly reduce or eliminate troubles with microphonics — thus far a serious problem. And because the detector surfaces fill a large fraction of the area of the arrays one can avoid losses associated with diffraction-limited Winston collectors.

We devote the following separate section to another improvement that is less obvious and relatively undocumented: instrumentation and techniques especially for extended objects.

5. INSTRUMENTATION FOR POLARIMETRY OF EXTENDED SOURCES

We have shown that the far-infrared/submillimeter polarization spectrum near intensity peaks is often strongly influenced by optical depth effects (see ref's 3 and 5 and notice the relatively low polarization at several intensity peaks in Figures 3, 4, and 5). To investigate the polarization spectrum in regions free of those effects and to determine the magnetic structure of entire clouds one must have a capability for accurate polarimetry over broad fields of view. But as one moves to fainter regions in extended sources, one must deal increasingly with the problem of unknown polarization in the reference beams. To determine the polarization at a point of interest, a "source point", one must know not only the flux density but also the degree and position angle of the polarization in the reference beams.

If photometric mapping shows that the flux density at the reference points is low enough, say, less than 10% of that at the source point, then, assuming a limiting range in the degree and angle of the polarization in the reference beams, one can often make an adequate estimate of the uncertainty in the polarization at the source point. A procedure for such estimates has been presented by Novak et al.[4] and by Schleuning et al.[5] But that procedure becomes less and less satisfactory as one moves to points where the source flux diminishes with respect to the reference flux.

A larger throw for the chopping secondary is, of course, an appealing concept but it is a concept with its own limitations. The CSO chopper, built by the University of Chicago, provides a relatively large (6 arcmin) throw. Nevertheless there are many cases where the reference beam problem is the limiting factor in mapping extended sources. We consider two aspects of the problem: first, how to analyze the data, and second how to minimize the errors.

5.1 Analysis

Where the chopper throw is sufficient to move the whole array off of a small source onto open sky one can analyze the data according to well documented procedures[9]. Where that is not possible the underlying procedure is the same. In either case a single measurement gives the difference in the Stokes parameters between a "source point" and reference points. The only difference is that on the extended source one must not assume that the Stokes parameters at the reference points are negligible. By making a series of measurements moving entirely across the source from open sky on one side to open sky on the other side one can measure a series of differences from which one can reconstruct the Stokes parameters, Q and U, and hence the polarization at each measured point. One reconstructs the Q's and U's separately using the same procedure as is used for flux densities (the I's). The reconstruction is carried out for each position on the sky. If necessary the process can be repeated from a new starting point until there are no gaps in the sky coverage.

5.2 Minimizing Errors

There are two sources of error that are encountered only in the case of extended sources. Each can be reduced by proper observing strategy.

The first is simply that errors accumulate as one derives parameters from differences in a series of measurements. It is therefore desireable to minimize the number of terms in the series. That is, one should use a large chopper throw and the chopping direction should be adjustable so that one can chop and step along the shortest dimension of the source. For example in the map of DR21 shown in Figure 5 it is clear that one should chop approximately in right ascension. For a similar ridge-like object oriented in an east-west direction one should chop approximately in declination

The second source of error has to do with the contrasting effects of atmospheric fluctuations on two components of the polarized flux reaching the detectors: first the component from the source as attenuated by the atmosphere and modified by the instrumental polarization; and second, the component emitted by the atmosphere and polarized by the same instrumental effects (the "polarized background flux"). The observations must be done in such a way as to remove the effect of the latter from the total polarized flux, leaving only the polarized signal from the source. That is usually accomplished to a satisfactory degree by chopping. If the polarized background flux were constant there would be no problem in polarimetric mapping of extended sources. One could, for example, first point at a fixed source position (without chopping) while modulating the total signal by rotating a halfwave plate. One would then move the telescope to a point entirely off of the source and again rotate the halfwave plate to determine the polarized background component.

But the background flux is not constant; it fluctuates over a wide range of time scales.. As the source flux is *reduced* by an increase in attenuation, the background flux and with it the polarized background flux will tend to *increase*. Moreover the background flux is generally much greater than the source flux. Even if the instrumental polarization is lower than the source polarization the polarized flux of the background may be much greater than the polarized flux one wishes to measure. One can take steps to minimize the problem but those who have successfully applied this technique have pointed out its limitations[19].

There are several possible combinations of halfwave plate rotation, chopping, nodding and changes in telescope pointing, but any that involve moving the telescope or waiting for the earth to turn by more than the chopper throw will be slow compared to the characteristic frequency, ν (a few Hz), of atmospheric fluctuations. Whatever combination is used it must include chopping, prefereably at ≥ 3 Hz.

The sequence of chopping, nodding, and stepping the halfwave plate described in §2 is satisfactory in principle but it is not the most efficient scheme. Integration time is lost while the halfwave plate is being moved and for a short period thereafter while waiting for the microphonics induced by the move to subside. In airborne astronomy with Stokes the integration efficiency was approximately 50%. With Hertz on the CSO the overall efficiency is about the same but a greater fraction of the loss is due to the time to nod the telescope.

To recover the time lost to stepping and to gain flexibility in the technique of making scans of extended objects it is desirable to pursue the following objectives:

1) Minimize vibrations associated with rotation of the halfwave plate and install detectors that are inherently resistant to vibrations so as to avoid micophonic noise.
2) Minimize all components of the instrumental polarization to assure manageable offsets and to avoid any modulation of the signal by inhomogeneities in the optical elements.
3) Provide a means to synchronize the rotation with the chopping and data aquisition.
4) Provide a signal processor that can properly analyze the waveform.

It is not yet clear whether the modulation due to the halfwave plate rotation should be faster or slower than the chopping frequency. If the choice is to go faster, the waveform would be approximately as shown schematically in Figure 7.

6. CONCLUSION

The polarimeter, Hertz, in its current configuration has the capability to measure scores of points in scores of sources. Improvements under consideration include replacing the current 32 pixel arrays with new-technology arrays with more pixels (~150) and much improved sensitivity; and introducing modifications of the mechanical, electronic, and analysis systems to allow continuous rotation of the halfwave plate. Results from Hertz have shown the importance of mapping large areas and the importance of spectropolarimetry at far-infrared and submillimeter wavelengths in widely spaced passbands from ~60 μm to 1300 μm and beyond. The design of Hertz and the plans for upgrades may serve as a guide for polarimeters at these wavelengths.

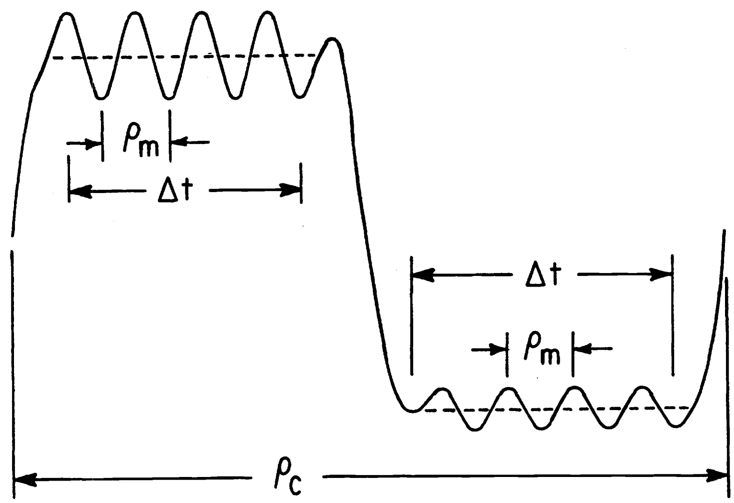


Fig 7 Schematic waveform for simultaneous chopping and rotation of the halfwave plate. (shown for negligible noise). P_C = chopping period. P_M = period of modulation of the polarization signal = 4 × period of halfwave plate = P_C/n where n = integer (probably ≥6). P_M is the same thoughout, but the amplitude and phase change between the "source" position (first half of the chopping cycle) and "reference" position (second half of chopping cycle). The signal is sampled during the periods marked Δt when the chopper is not moving. An alternative is to choose $P_M \ll P_C$.

7. ACKNOWLEDGEMENTS

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